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Vibrotactile Sensitivity of the Head

by Kimberly Myles and Joel T. Kalb

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14. ABSTRACT

The brain rarely processes events of the physical world using signals from a single sensory modality. While the visual and auditory modalities are considered frequently in communication research, the tactile modality is considered the least as a possible mode of communication. In addition, previous studies of tactile sensitivity and solutions in utilizing the tactile modality have been focused on torso and limb locations. However, there are currently no tactile sensitivity data for the head. The goal of the present study was to investigate tactile sensitivity of the various locations on the head and the effect of signal frequency on the tactile threshold. An adaptive psychophysical procedure was used to determine differences in tactile sensitivity at various points on the head. Obtained results indicate that the crown of the scalp is less sensitive to vibration than the areas near the forehead, temples, and lower part of the back of the head.

15. SUBJECT TERMS

head tactile display, tactile sensitivity, vibrotactile thresholds

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1. Introduction

The brain rarely processes events of the physical world using signals from only one sensory modality. Instead, it simultaneously processes signals received by several sensory modalities from which it is able to interpret what is going on around us (Moorhead et al., 2004). "Well-designed multimodal systems integrate complementary modalities to yield a highly synergistic blend in which the strengths of each mode are capitalized upon and used to overcome weaknesses in the other" (Oviatt, 1999, p. 74). Multimodal systems are also designed to prevent information overload from occurring for any one sensory modality, as well as, provide a solution for allowing the user to instinctively use the different input modes as needed (Oviatt, 2001). Use of the skin as an information channel can be beneficial within a system when the visual and/or auditory modalities are overloaded (Raj et al., 2000). However, in the area of system design, touch is considered the least as a possible mode of communication for enhancing situational awareness (SA) and performance while the visual modality is considered the most (Moorhead et al., 2004).

Previous research studies have shown that touch is an excellent mode of communication and designers are exploring a number of opportunities afforded by the tactile modality to enrich the connection with the environment. For example, use of the tactile modality has been beneficial in improving safety for car drivers (Suzuki and Jansson, 2003; van Erp et al., 2002; van Erp and van Veen, 2001). Specifically, Ho et al. (2005) have shown the potential benefit of using the tactile modality in cars to impart warning signals that communicate the presence of an impending accident. Additionally, Chan et al. (2008) have shown the benefits of using the tactile modality to support turn-taking in remote collaboration among groups. Potential applications for the military environment include using the tactile modality to distribute information about auditory and other events. For example, by using information from mortar or sniper detection systems, the Soldier could be cued via tactile signals regarding the direction and location of the event source. Furthermore, the tactile modality could be used to indicate movement direction in GPS-supported navigation.

The focus of the authors' current research program involves evaluating the use of touch as a viable input modality for new and existing military equipment rather than exploring combinations of visual or auditory modalities to increase soldier performance. There is potential for integrating the tactile and auditory modalities in one communication system by using current bone conduction (BC) transducers for both speech and tactile signals on a time-sharing basis. Bone conduction systems transmit sound energy through bony tissue in the skull, via vibrators mounted on the head, which stimulates the cochlea (resulting in an auditory sensation) while bypassing the external ear and eardrum (Henry and Letowski, 2007). Because the BC transducers are for use on the head, a likely extension of the transducers is the use of the same

transducers in a head tactile communication system. If successful, Soldiers would benefit from a head-mounted tactile display (designed in conjunction with BC headgear or as a stand alone device) that could be used for directional cueing with very little additional equipment and weight to carry.

However, current research reporting tactile sensitivity measures and practical solutions using the tactile modality is exclusively dedicated to the finger (Morioka et al., 2008; Rabinowitz et al., 1987; Stuart et al., 2003; Wilska, 1954), hand (Verrillo, 1962), arm/forearm (Cholewiak and Collins, 2003; Morioka et al., 2008; Piateski and Jones, 2005; Stuart et al., 2003; Verrillo, 1966; Wilska, 1954), torso (Piateski and Jones, 2005; van Erp, 2005; van Erp and Werkhoven, 1999; Wilska, 1954), wrist (Ferris and Sarter, 2008), shoulder (Stuart et al., 2003; Wilska, 1954), cheek (Stuart et al., 2003), thigh/chin/forehead (Wilska, 1954), foot (Morioka et al., 2008; Nurse and Nigg, 1999), and toe (Morioka et al., 2008; Wilska, 1954). There are currently no tactile threshold data for the head and such data are needed to ensure that tactile systems designed for the head are compatible with the sensitivity of the user. The extent to which vibrotactile[*] stimulation of the head is viable as a method of communication depends on determining what and how much information can be perceived on the head (Lambert, 1990).

The purpose of this study was to determine (1) vibrotactile thresholds associated with the perception of tactile stimuli applied to the head and (2) a relative pattern of vibrotactile sensitivity for the head.

2. Method

2.1 Participants

Twelve Marines were recruited for this study. All participants were male with standard military haircuts. One participant's data was identified as an outlier because the participant answered "Yes" for each trial which consistently placed the participant's data at the maximum attenuation of the ZEST procedure. Consequently, the data were not usable. For the remaining 11 participants, the mean age of participants was 21 years (*SD* = 2.45).

2.2 Experimental Design

A 7 × 3 within-subjects design was used to determine the effect of Head Location and Frequency on vibration thresholds for the head. A 2-factor repeated measures analysis of variance (ANOVA) was used to analyze differences in vibration thresholds at an alpha level of 0.05.

[*] Vibrotactile is the sense of touch associated with vibration.

- Independent Variables:
    - Head Location (CZ, F3, F8, T4, O2, T3, PZ)
    - Frequency (32 Hz, 45 Hz, 63 Hz)
- Dependent Variable: Vibration Threshold

2.3 Head Locations

The locations of the head chosen for this study follow the 10-20 system of electrode placement used for high-density electroencephalography (EEG) studies. Figure 1 illustrates the scalp topography of the 10-20 system of electrode placement. The vertex (CZ), and temple (T3, T4) locations were chosen based on optimal BC vibrator placement (McBride et al., 2005) and F3, F8, PZ, and O2 were chosen so that the location sample would be representative of a whole-head mapping. The locations were also chosen such that each lobe of the cerebral cortex was represented.

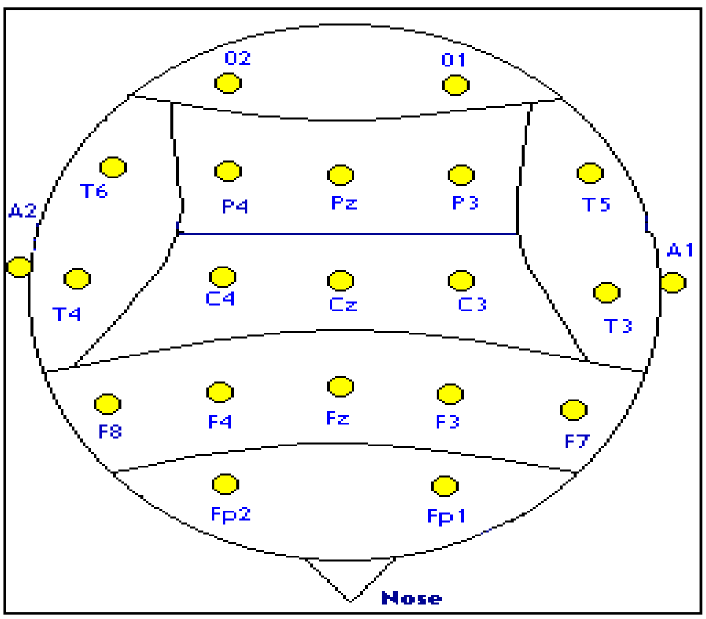

Figure 1. The 10-20 system of electrode placement. (Adapted from D. G. Domenick, 1998 http://members.aol.com /aduial/1020fc.html.)

2.4 Frequency

Pilot testing was conducted to determine the optimal frequency ranges to use in this study. Pilot results showed evidence of both tactile and auditory perception of the signal for tactile signals that contained frequencies above 64 Hz. For tactile signals containing frequencies below 64 Hz, only tactile perception of the signal occurred. Thus, to report vibration thresholds that did not contain auditory interference, signals needed to be below 64 Hz.

2.5 Vibration Threshold Measurement

To determine vibration threshold levels (i.e., the smallest amplitude at which an observer felt vibration), the Zippy Estimation by Sequential Testing (ZEST) psychophysical adaptive procedure was used (King-Smith et al., 1994; Watson and Pelli, 1983). Thresholds obtained using ZEST is based on a participant's past performance and the use of this history makes it possible to estimate thresholds quicker and with a smaller number of trials than other traditional psychophysical methods. Thus, for this reason, ZEST is considered an efficient method for obtaining sensitivity thresholds.

The ZEST procedure was used to find threshold values for each of the treatment conditions. Each of the 21 treatment conditions (Head Location × Frequency) was presented 10 times. A starting attenuation in the middle of the range (8–40 dB) was presented on the first trial. Based on the participant's response for the first trial, ZEST estimated a new attenuation. If the participant's response was "No" (I do not feel the stimulus), the attenuation was reduced on the second trial. In contrast, if the participant's response was "YES" (I feel the stimulus), the attenuation increased on the second trial. The participant's responses from both trials 1 and 2 were again considered for a new attenuation for trial 3. This sequence was repeated for every trial within a treatment until the last response for that treatment was collected. The last response obtained on trial 10 was recorded as the vibration threshold for that treatment within a 1-dB error. In addition, the range of signal attenuation and the choice of using 10 trials per treatment for the ZEST procedure were determined based on pilot test data.

2.6 Apparatus and Stimuli

The C-2 tactor designed by Engineering Acoustics, Inc. (EAI) (www.eaiinfo.com) was used for this study. The C-2 tactor is 1.2 in (diameter) × 0.31 in (height) and weighs 17 g. The tactor is designed with a moving contactor surface (0.3 inch in diameter). When electrical energy is applied (i.e., sine wave) the contactor oscillates perpendicular to the skin (Mortimer et al., 2007; van Erp, 2002) (figure 2). Seven tactors were placed in a headband (figure 3) designed to hold one tactor at each chosen head location and the static force was uniform across all tactors. The tactors were measured to confirm that each tactor was capable of producing similar tactile output and each tactor was found to be within plus or minus 2dB of the mean (see figure 4 in Kalb et al., 2008).

Figure 4 shows a diagram of the equipment used for this study in which the computer generated a modulated sinusoidal carrier wave with a 10-V peak amplitude. Each stimulus contained a cycle period of 250 ms, a duty cycle fraction of 0.25, and three repetitions extending the stimulation period of the signal to 750 ms (figure 5). Furthermore, the signal was divided into three equal phases during the on time of the duty cycle, namely the rise, sustain, and fall. Rise and fall both followed a half cosine response while sustain was at full modulation. The signal was then attenuated by the ZEST procedure, sent to one of seven multiplexer channels, and amplified by a unity-voltage-gain power-driver which was connected to a tactor.

Figure 2. The C-2 tactor.

Figure 3. Headband designed to hold C-2 tactors.

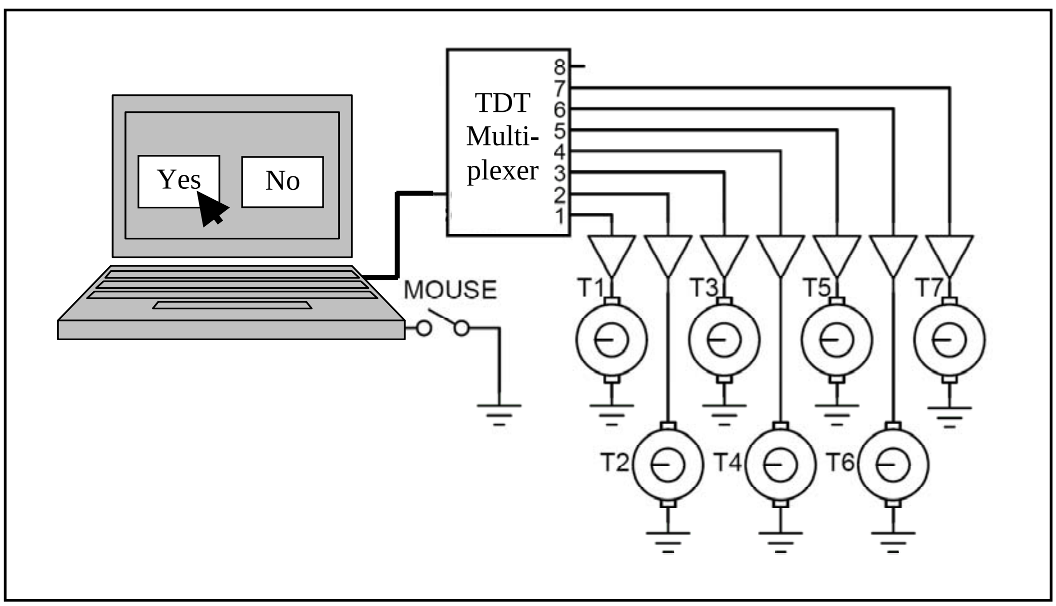

Figure 4. Diagram of equipment showing Tucker-Davis Technologies System II (TDT) and the seven tactors.

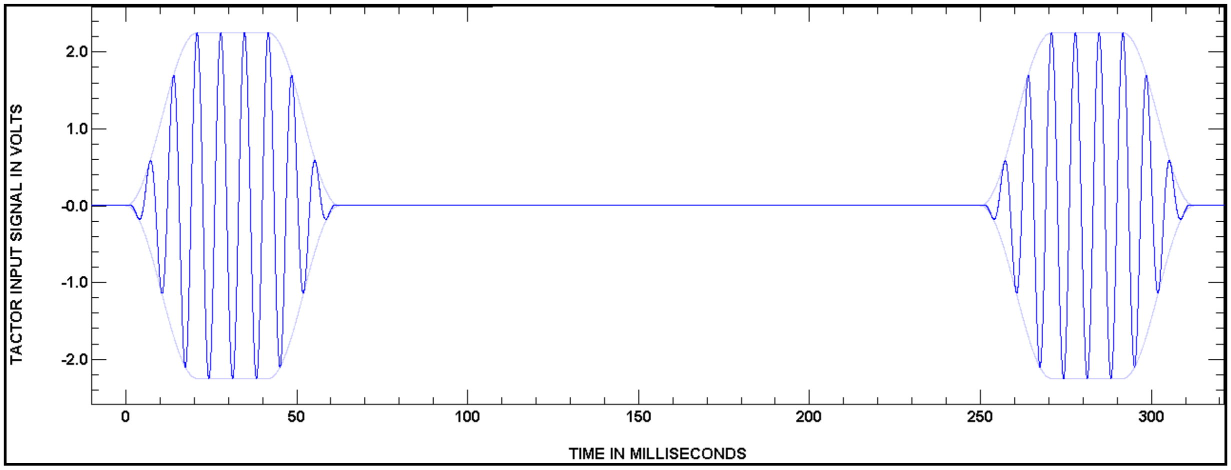

Figure 5. Diagram of the signal.

2.7 Procedure

Participants were seated in a standard office chair in an Industrial Acoustics Company (IAC) sound attenuating chamber and provided a consent form to review and sign if they agreed to participate. Next, the experimenter placed a stretchable headband on the participant's head (secured with Velcro fasteners) and examined the headband to ensure that the tactors made proper contact with the scalp. Participants received a total of 210 vibrating stimuli on the head. Each treatment was presented ten times and each head location was tested one at a time. For each stimulus, participants indicated if they felt or did not feel a vibrating sensation on the head by using a mouse to click a "YES" button if they felt a vibrating sensation and a "NO" button if they did not feel a vibrating sensation. Prior to starting the experiment, the experimenter checked that each tactor was emitting a vibration stimulus which also served as practice trials to familiarize the participants with the task.

3. Results

Expressed as a voltage level referenced to a 1-V peak, the full stimulus of a 10-V peak was equivalent to a level of 20 dB. This level was then reduced by ZEST attenuations in response to the participant action and recorded accordingly. For example, a 30-dB attenuation yielded a –10 dB level at the tactor. Table 1 shows the means and (standard deviations) of these voltage levels at all locations and frequencies. An insensitive location required significantly more stimulation for detection than a more sensitive location, thus, more voltage was required at the tactor to produce an increase in displacement (i.e., less attenuation).

Table 1. Means and (standard deviations) for vibration thresholds in dB re: 1 Vp.

	Frequency		
Head Location	**32 Hz**	**45 Hz**	**63 Hz**
CZ	0.84 (7.60)	1.70 (7.32)	2.00 (6.86)
F3	0.67 (5.85)	0.86 (6.08)	0.81 (5.81)
F8	–1.85 (8.59)	–0.79 (7.71)	–0.61 (7.53)
T4	–3.69 (4.83)	–3.30 (5.18)	–1.99 (5.73)
O2	–6.48 (4.95)	–5.06 (4.13)	–4.62 (4.10)
T3	–6.36 (4.18)	–5.59 (3.71)	–5.29 (3.69)
PZ	–8.04 (6.18)	–8.22 (6.00)	–7.85 (6.68)

An ANOVA revealed a significant main effect for Head Location, F (6, 60) = 4.35, p = .001 and Frequency, F (1.21, 12.11) = 6.02, p = 0.03 (figures 6 and 7, respectively).[*] No significant main effect was found for the Head Location × Frequency interaction, F (12, 120) = .82, p = .63. Post hoc comparisons (LSD) revealed that PZ (M = –8.04 dB) was significantly more sensitive to vibrotactile stimulation than CZ (M = 1.51 dB), p <0.01. In figure 6, head locations are arranged from least to most sensitive and the remaining significant comparisons revealed that the three least sensitive head locations (CZ, F3, and F8) were significantly different from the three most sensitive head locations (O2, T3, and PZ). Location T4 was the neutral location which was not significantly different from any of the other head locations. Post hoc comparisons (LSD) also revealed that thresholds at 45 and 63 Hz were significantly higher than thresholds at 32 Hz (M = –3.56), p <0.05 (figure 7). Thresholds at 45 Hz (M = –2.92 dB) and 63 Hz (M = –2.51 dB) were not significantly different from one another.

For level conversion from tactor voltage to displacement, we combined known fingertip displacement thresholds (Lamoŕe and Keemink, 1988) with measured tactor voltage levels at the finger to obtain a transfer relationship shown in Kalb et al. (2008). This revealed a second order low-pass response with an 11.5 dB (referenced to 1 μ/V) gain below 100 Hz. Assuming that the tactor displacement for a given voltage is the same regardless if the tactor is touching the fingertip or the head[†], we converted our voltage thresholds to displacement levels by adding 11.5 dB. Figures 8 and 9 show these thresholds.

[*]Mauchly's Test of Sphericity (p = .009) revealed that frequency violated the sphericity assumption; thus, the Greenhouse-Geisser correction was used to adjust the df.

[†]This is true if the skin input impedance is at least ten times higher than the tactor output impedance (Mortimer et al., 2007).

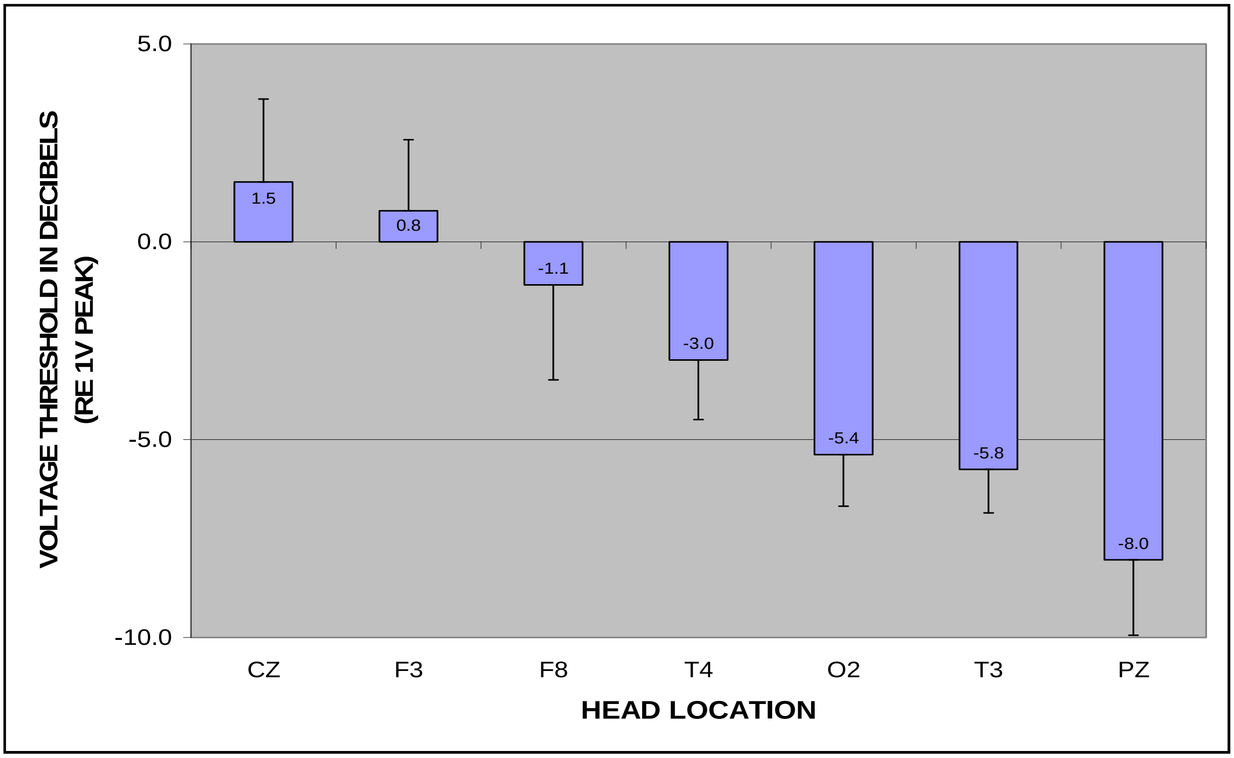

Figure 6. Mean threshold by head location. (The error bars indicate standard errors.)

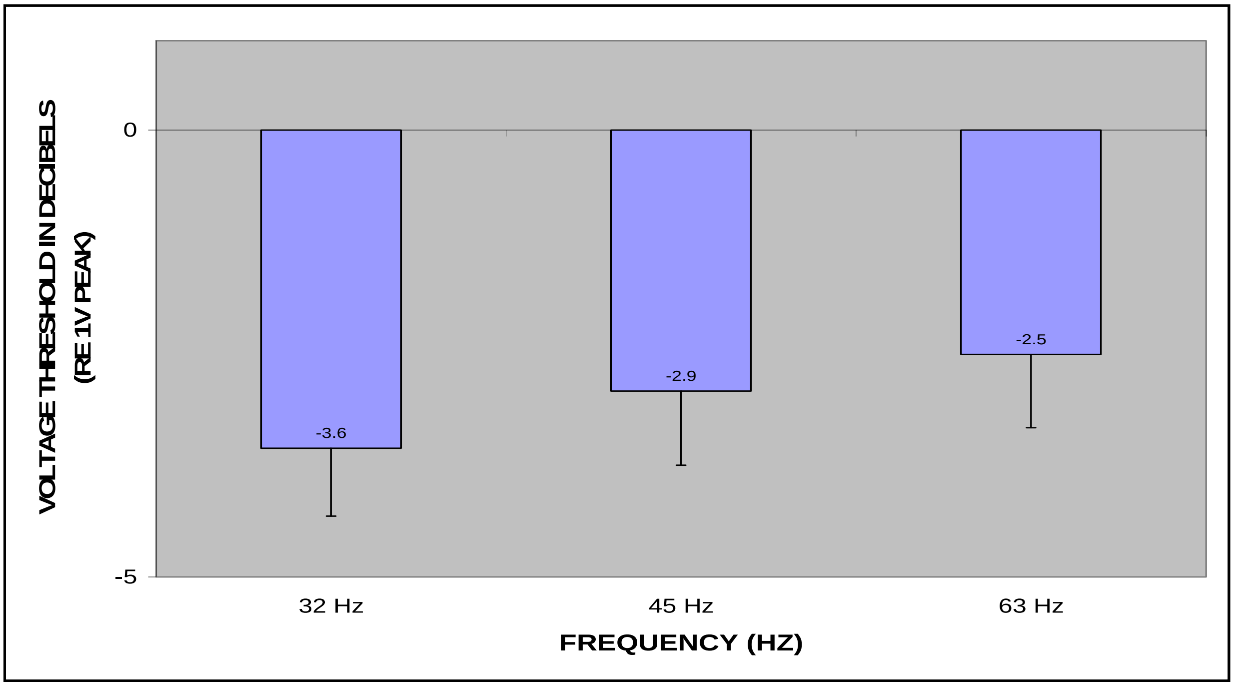

Figure 7. Mean threshold by frequency. (The error bars indicate standard errors.)

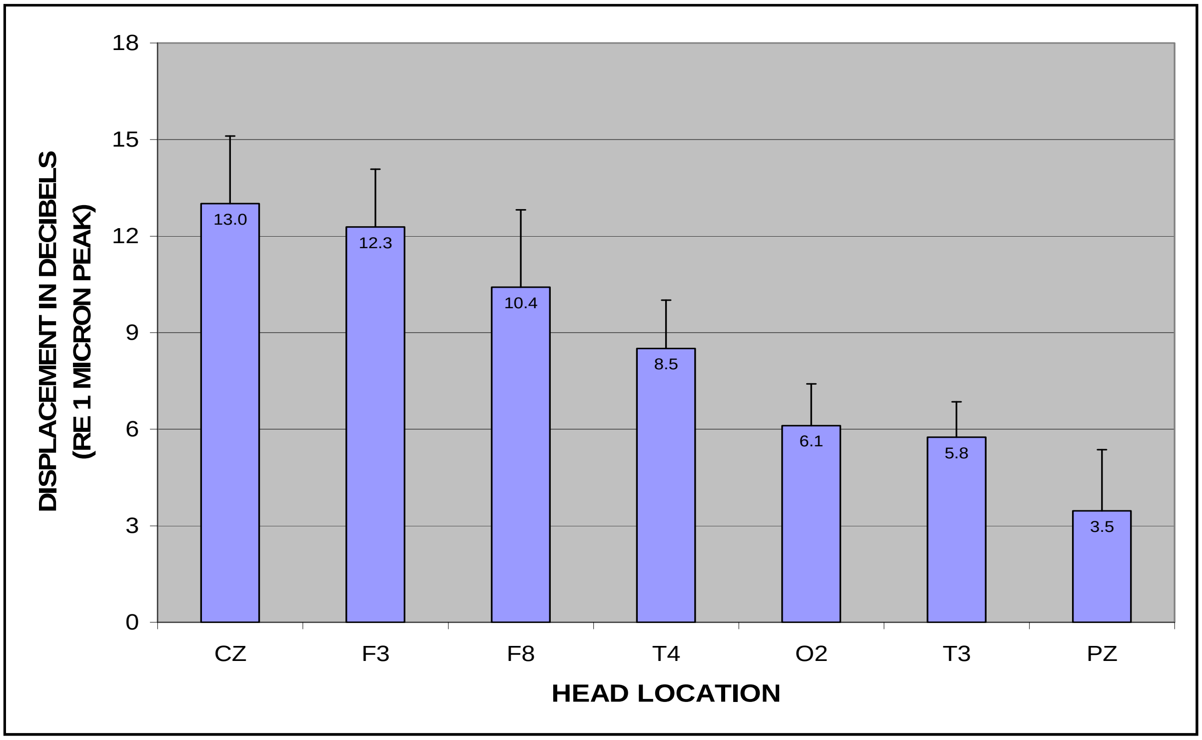

Figure 8. Mean displacement by head location. (The error bars indicate standard errors.)

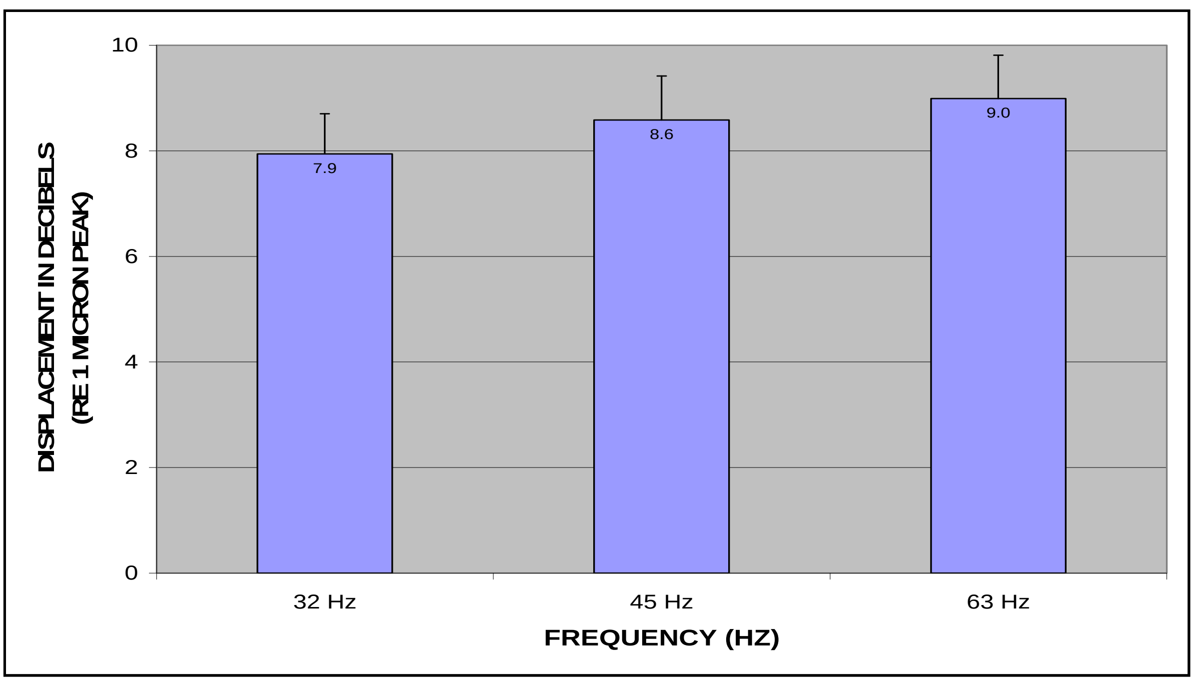

Figure 9. Mean displacement by frequency. (The error bars indicate standard errors.)

4. Discussion

Due to the very limited information available regarding tactile sensitivity of the head, the authors made no prior hypothesized assumptions about the outcome of the data. The most revealing information in the literature regarding the pattern of tactile sensitivity for the head was published by Weber (1834/1978) which suggests that all areas of the scalp are not equally sensitive and the crown is less sensitive than the skin near the forehead, temples, and lower part of the back of the head. The thresholds found in this study are in agreement with the pattern of scalp sensitivity proposed by Weber (1834/1978). A significant finding for the main effect of Head Location suggests that vibration sensitivity is different for the seven head locations in this study. Furthermore, the crown (CZ) was found to be the least sensitive to vibration stimuli relative to T3, T4 (the temples) and PZ, O2 (back of the head).

The back of the head (O2) was found to be more sensitive than the front of the head (F3, F8)*. This difference in sensitivity was 5 dB. PZ was found to be the most sensitive to vibration stimuli relative to the other head locations included in this study. The difference in sensitivity between PZ and the back of the head (O2), the sides of the head (T3, T4), and the front of the head (F3, F8) was 3 dB, 4 dB, and 8 dB, respectively. Gilliland and Schlegel (1994) found that participants were able to detect 100% of low- and high-intensity vibration stimuli presented to the parietal region of the scalp. Thus, it may be true that the other locations in the parietal region of the head (P4 and P3 found in figure 1) are just as sensitive as PZ but further studies would be required to confirm such a claim. Weinstein (1968) reported that skin sensitivity is generally the same for both the left and right sides of the body. The same may be true for sensitivity on the head as the vibration threshold for the left temple (T3) was not significantly different from the vibration threshold for the right temple (T4). Also, vibration thresholds for F3 and F8 were not significantly different as F3 is located within the left hemisphere of the scalp and F8 is located within the right hemisphere of the scalp. In addition, the difference in sensitivity between the left side of the head (F3, T3) and the right side of the head (F8, T4, O2) was 0.8 dB.

There are no other studies that report tactile or vibration thresholds for different locations on the head. In general, the thresholds reported in this study are lower than those reported by Wilska (1954) at similar frequencies on the forehead, however it is known that tactile sensitivity thresholds are affected by a number of tactor characteristics, specifically contactor size and the presence or absence of a surround (Lamoŕe and Keemink, 1988; Stuart et al., 2003). Although we found significance for the main effect of Frequency, the differences between the thresholds at

*General sensitivity for the front of the head was calculated as the average sensitivity of F3 and F8.

the tested frequencies is so small that the data is still in agreement with Verrillo (1966) who found that thresholds were essentially the same for frequencies between 25 and 40 Hz for hairy skin.

5. Conclusions

The measures found for vibration sensitivity in this study confirm the general pattern of sensitivity for the scalp reported by Weber (1834/1978). In addition, this study extends the general pattern of sensitivity for the scalp by providing objective measures that demonstrate the pattern. Of the seven chosen locations, PZ appears to be the best location for presenting vibrotactile information on the head because it is the most sensitive to vibration stimuli, followed by the temples (T3, T4) and O2. In fact, the entire parietal region may be the most sensitive region of the scalp however additional studies are needed to confirm this hypothesis. These findings may be beneficial in designing a head-mounted tactile display to support a directional cueing system to alert Soldiers to important events in the environment.

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Appendix. Head Diagram With Displacement Sensitivity Values (Decibel Referenced to 1 µm)

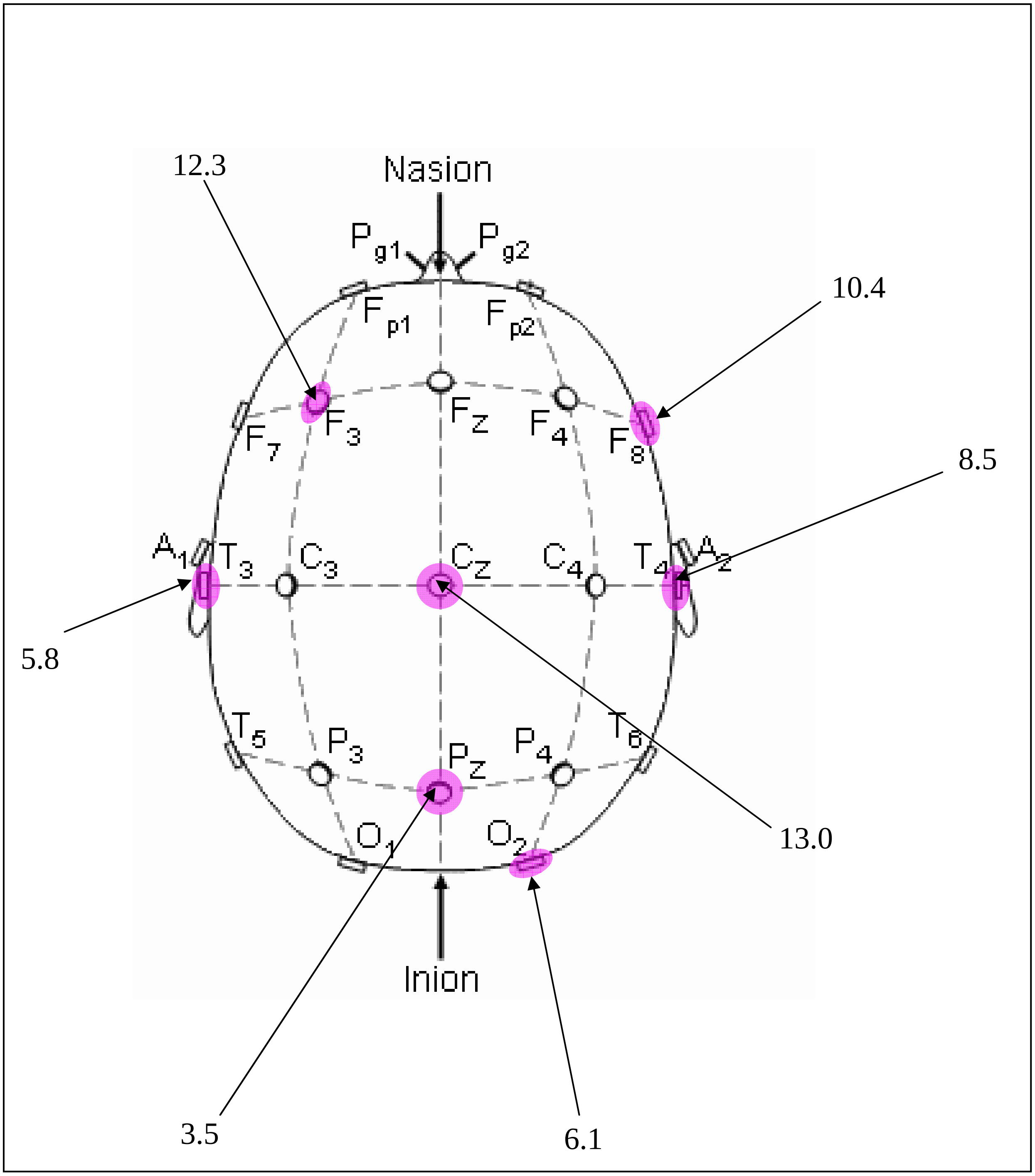

Figure A-1. Head diagram with displacement sensitivity values (decibel referenced to 1 μm).

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